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Biological Resources of the Louisiana Coast: Part 2. Coastal Animals and Habitat Associations

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ABSTRACT

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The productivity of biological resources in coastal Louisiana is at risk because of Gulf shoreline changes. Most estuarine species depend on Gulf shores and barrier islands for nesting, food, or shelter and will be directly affected by habitat loss. Others have complex indirect relationships with the shoreline ecosystem. Forecasting the degree of impact on all animals that are indirectly affected by shoreline change cannot be done with any degree of certainty. However, it is possible to evaluate and attempt to quantify the effects of changes in environmental factors that drive the distribution and abundance of commercial, keystone, and endangered species. Our objective was to provide an overview of habitat associations and environmental concerns for these significant animal species. For example, many important commercial species in Louisiana—such as blue crabs, Gulf menhaden, and various shrimp species—move among coastal habitats to complete parts of their life cycles. If the movement of these animals from the Gulf through tidal passes into estuarine nursery habitats is altered by shoreline changes, then populations of these species will be put at risk. Likewise, populations of keystone species, such as the common Rangia clam and the American oyster, will be affected if shoreline loss leads to changes in salinity conditions. Finally, most of Louisiana's threatened and endangered coastal species—such as sea turtles, brown pelicans, piping plovers, and Gulf sturgeon—rely on vulnerable barrier island habitats. Information on estuarine invertebrates, fishes, and other coastal animals is provided so that restoration of essential habitats can be incorporated into coastal management activities.

ADDITIONAL INDEX WORDS: *Shoreline changes, habitat loss, habitat alteration, estuarine ecosystems, commercial species, keystone species, endangered species, coastal management.*

INTRODUCTION

A principal characteristic of Louisiana's estuarine animal communities is their high productivity (CHESNEY, BALTZ, and THOMAS, 2000; DARDEAU *et al.,* 1992). Nutrient input from the Mississippi River and other coastal rivers acts in combination with shallow-sloped aquatic habitats and a long growing season to provide conditions that maximize growth and reproductive output for most estuarine animals (BALTZ, THOMAS, and CHESNEY, 2003; CHESNEY, BALTZ, and THOMAS, 2000; DARDEAU *et al.,* 1992). Productivity is also enhanced because of ecotones that exist in areas of interface among the inland freshwater systems, estuarine systems, and offshore marine systems of coastal Louisiana. Estuarine animals have evolved life histories that allow them to exploit these ecological transition zones that form along gradients of environmental variables. For example, most commercially important species such as blue crabs (*Callinectes sapidus*), Gulf menhaden (*Brevoortia patronus*), and various penaeid shrimp require many different habitats as they develop from egg to adult, utilizing multiple ecotones throughout their life cycles to exploit resources found in different ecosystems. Animals that rely on having access to a variety of estuarine habitats to complete their life cycles are referred to as being "estuarine dependent" (THOMPSON and FITZHUGH, 1985). Without the diversity of habitats, ecotones, and environmental gradients that is created and protected by the physical presence of barrier islands and intact shorelines, the considerable productivity associated with these important estuarine-dependent communities would be greatly diminished.

The tolerance of life history stages to salinity differences along the freshwater to marine gradient also controls animal distribution and abundance. The mobile nekton community rapidly shifts its geographic position along the estuarine gradient. However, sessile organisms cannot move and local populations decline with long-term salinity changes, but mobile larvae will slowly colonize areas of appropriate salinity. Two keystone animals that are included in this category are the Rangia clam (*Rangia cuneata*) and the American oyster (*Crassostrea virginica*). Both species act as "biofilters" in their estuarine habitats, provide valuable hard substrate for other organisms, and serve as prey items for numerous predators (VAUGHN and HAKENKAMP, 2001; ZIMMERMAN *et al.,* 1989). For these species, salinity is a strong predictor of where they will occur and thrive within the estuary. Because Rangia clams and American oysters require specific environ-

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mental conditions, their populations would be threatened should existing salinity conditions change significantly because of shoreline changes or loss of barrier islands. For example, changes in the Barataria Basin resulted in increased salinity intrusion and eutrophication that, in turn, led to a reduction of optimal nursery habitats available for oysters (DARDEAU *et al.,* 1992). If local conditions are not conducive to the survival of these keystone species and they decline, then many other estuarine organisms that depend on them will also decrease.

Another group of coastal animals that is threatened by coastal shoreline changes includes those species that rely on barrier island habitats to complete their life cycles. Beyond their role as protectors of complex and productive aquatic habitats, barrier islands provide their own unique habitats for animals in the form of long reaches of high-energy sand beaches, dunes, marshes, and beds of submersed aquatic vegetation (SAV) located in shallow nearshore habitats (WILLIAMS, PENLAND, and SALLENGER, 1992). The fact that these islands are not connected to mainland shoreline also means that predation pressure is far reduced in these habitats. Animals that use barrier islands include most of the federally threatened and endangered species found in coastal Louisiana including the brown pelican (*Pelecanus occidentalis*), the piping plover (*Charadrius melodus*), the Gulf sturgeon (*Acipenser oxyrinchus desotoi*), and six species of sea turtles. These species cannot easily find similar island conditions in other regions of Louisiana's mainland shoreline. Should barrier islands disappear because of erosion and a lack of sediment replenishment from rivers, the rare animals that use these habitats would also disappear from coastal Louisiana.

This paper will provide a review of some important Louisiana coastal animals and their habitat associations. Our purpose is to show how barrier island loss and rapid shoreline changes pose a risk to many of these species because the habitat conditions under which they thrive will be altered. First, we will focus on the many commercially important invertebrates and fishes that are estuarine dependent and rely on moving through natural connections among various coastal habitats to complete their life cycles. Then we will discuss keystone species that require specific salinity conditions to survive and provide a stable ecological base for other animals in the local community. Finally, we will examine those federally threatened and endangered species that use barrier islands to complete their life cycles and face extermination should these habitats disappear. We will show that increased shoreline change not only jeopardizes the infrastructure of coastal Louisiana (*i.e.,* cities, roads, and so on) but also threatens to significantly alter the many biological resources associated with coastal ecosystems.

COMMERCIAL SPECIES AND ESTUARINE DEPENDENCE

Many coastal aquatic animals use estuaries as nursery habitats, although it is difficult to directly quantify the relationship between local environmental conditions and the success of a species (ABLE and FAHAY, 1998). Historically, these species have been termed "estuarine dependent" because they appear obligated to use estuarine habitats to complete their life cycles (GILLANDERS *et al.,* 2003; HOSS and THAYER, 1993; THOMPSON and FITZHUGH, 1985). By using estuaries during their early life stages, estuarine-dependent species may increase survivorship because these habitats offer more protection from predation and damaging wave action (ABLE and FAHAY, 1998; MINELLO, 1993; MINELLO and ZIMMERMAN, 1983). Another benefit of estuarine use is access to increased food sources (TURNER and BRODY, 1983; ZIMMERMAN *et al.,* 2000). This need for a protected nursery habitat with high local productivity is especially crucial for key commercial species. For example, a study that analyzed 21 years of coastal Louisiana fishery data revealed that 9 of the 10 most abundant fishery species collected by trawls (including invertebrates and fishes) were estuarine dependent (CHESNEY, BALTZ, and THOMAS, 2000). Without access to estuaries during their early life stages, populations of commercial and recreational species such as brown shrimp (*Farfantepenaeus aztecus*), white shrimp (*Litopenaeus setiferus*), blue crab (*C. sapidus*), Gulf menhaden (*B. patronus*), Atlantic croaker (*Micropogonias undulatus*), and spotted seatrout (*Cynoscion nebulosus*) will likely decline over time. Shoreline change threatens these important species by altering existing routes of inshore movement for juvenile animals. One illustration of this problem is the possibility of increased coastal erosion leading to the loss of barrier islands. Without the physical presence of barrier island passes, landward currents would not be focused or increased in defined, restricted regions (*i.e.,* inlets), resulting in an overall reduction in tidal prism (HEALY, COLE, and DE LANGE, 1996). This, in turn, would decrease the chances that drifting larval fishes, crabs, and shrimp would reach essential inshore habitats. Therefore, we will examine the habitat associations and life histories of key commercial species on a species-by-species basis to show how shoreline change may impact each. Although our analyses will be restricted to a few common commercial species, it can be assumed that these estuarine-dependent animals serve as accurate surrogates for the management of all aquatic species that use estuarine habitats in coastal Louisiana.

We will first focus on the habitat associations of three commercially important invertebrates (brown shrimp, white shrimp, and blue crabs). It is also necessary to recognize that many other demersal and nektonic invertebrates would be affected by shoreline change (Table 1). For example, other species such as pink shrimp (*Farfante duorarum*) and stone crabs (*Menippe adina*) are also harvested commercially, though in higher-salinity areas and their catch is relatively small compared to these other species. Other noncommercial estuarine invertebrates in Louisiana include animals in over 20 diverse animal phyla (GOSNER, 1971). Major groups include sponges, hydroids, jellyfish, ctenophores, flatworms, nemertines, roundworms, polychaetes, mollusks (snails, clams, squid), crustaceans (shrimp, crabs, amphipods, copepods), echinoderms (brittle stars, starfish, sea cucumbers), and chordates (sea quirts, lancelets). While most of these species are small (<1 cm) with soft bodies, because of their abundance they have significant effects on estuarine processes through their diverse feeding adaptations and consumption

Table 1. *Selected commercially and recreationally important species found in coastal Louisiana (LA) that are estuarine dependent. Estuarine-dependent species are those animals that use estuarine habitats during at least one stage of their life cycle.*

Group Common Name (Scientific Name)	Commercial Significance	Description of Estuarine Dependence
Invertebrates		
Brown shrimp[1] (*Farfantepenaeus aztecus*)	Most productive shrimp fishery species in Gulf of Mexico; LA leads Gulf states[2,3]	Postlarvae and juveniles require inshore nursery habitats, preferably with vegetation
White shrimp[1] (*Litopenaeus setiferus*)	Second most productive shrimp fishery species in Gulf of Mexico; LA leads Gulf states[2,3]	Postlarvae and juveniles require inshore nursery habitats, preferably with vegetation
Blue crab[1] (*Callinectes sapidus*)	Most productive commercial crab species in US; LA leads US in landings (31% of US total)[3]	Juveniles require inshore nursery habitats; adults spawn in estuaries
Pink shrimp (*Farfante duorarum*)	Third most prouctive shrimp fishery species in Gulf of Mexico; LA leads Gulf states[2,3]	Postlarvae require inshore nursery habitats, preferably with vegetation
Vertebrates		
Gulf menhaden[1] (*Brevoortia patronus*)	Most productive finfish fishery in US (all menhaden species); LA leads Gulf states[4]	Larvae and juveniles use inshore nursery habitats
Atlantic croaker[1] (*Micropogonias undulatus*)	Only US finfish in top 10 most abundant species both commercially and recreationally[5]	Larvae and juveniles use inshore nursery habitats
Spotted seatrout[1] (*Cynoscion nebulosus*)	Most popular recreational food fish in LA[6]	Larvae and juveniles use inshore nursery habitats; adults spawn in deep passes
Spot (*Leiostomus xanthurus*)	Fourth most numerous finfish collected in long-term fishery-independent sampling[7]	Larvae and juveniles use inshore nursery habitats
Red drum (*Sciaenops ocellatus*)	Species has widespread recreational and culinary interest within LA	Juveniles and adults use shallow barrier island habitats
Striped mullet (*Mugil cephalus*)	Small Louisiana commercial fishery; important prey species	Juveniles use inshore nursery habitats
Sand seatrout (*Cynoscion arenarius*)	Valuable recreational fishery species	Juveniles use inshore nursery habitats
Black drum (*Pogonias cromis*)	Valuable commercial and recreational species throughout Gulf of Mexico	Juveniles use inshore nursery habitats (though tolerant to wide salinity range)
Sheepshead (*Archosargus probatocephalus*)	Valuable recreational fishery species	Adults feed in bays and estuaries
Southern flounder (*Paralichthys lethostigma*)	Valuable commercial and recreational species throughout Gulf of Mexico	Juveniles use estuaries, brackish water, and freshwater creeks

[1] Species described in text.
[2] NMFS (1999).
[3] NMFS (2003).
[4] VanderKooy and Smith (2002).
[5] NMFS (2002).
[6] Baltz *et al.* (2003).
[7] Chesney *et al.* (2000).

of algae, wetland detritus, and other organic material (Day, Hall, and Yanez-Arancibia, 1989). High populations, maintained by rapid growth and reproduction, provide abundant food for fish and wildlife. Feeding and burrowing activities, plus the production of skeletons, mucus, feces, and pseudofeces, help modify local sediments, sediment deposition, and erosion rates. These small species are generally of little concern to environmental managers, but their connections and roles in the estuarine ecosystem make them as vulnerable to the impacts of shoreline change as other, more recognized animals.

Brown shrimp support the largest shrimp fishery in the Gulf of Mexico (Chesney, Baltz, and Thomas, 2000; Zimmerman, Minello, and Rozas, 2000). Its habitat associations reveal how shoreline change poses as a potential threat to fisheries. As with other estuarine-dependent species, the brown shrimp life cycle begins offshore. Hatching occurs in deep (up to 100 m depth) marine habitats in spring and early summer with fertilized eggs becoming free-swimming larvae (Turner and Brody, 1983). While growing and undergoing several molts, these larvae rely on timed use of inshore currents to transport them to estuarine nursery habitats (Figure 1) (McTigue and Zimmerman, 1991; Turner and Brody, 1983).

Once inshore, brown shrimp postlarvae are more commonly associated with vegetated habitats (either emergent marshes or beds of SAV) than nonvegetated areas (Zimmerman, Minello, and Rozas, 2000). The benefits of this habitat association are twofold in that these vegetated habitats offer both increased resources for growth and protection from potential predators (Turner and Brody 1983; Zimmerman, Minello, and Rozas, 2000). During the summer, postlarval and juvenile brown shrimp feed omnivorously on prey items including benthic infauna (*e.g.,* annelid worms, peracarid crustaceans), epiphytic algae, marsh detritus, and various plant and animal materials (McTigue and Zimmerman, 1991; Zimmerman, Minello, and Rozas, 2000). Although generalist feeders, juvenile brown shrimp appear to rely most heavily on having access to infaunal worms to support their growth (McTigue and Zimmerman 1991). After reaching a

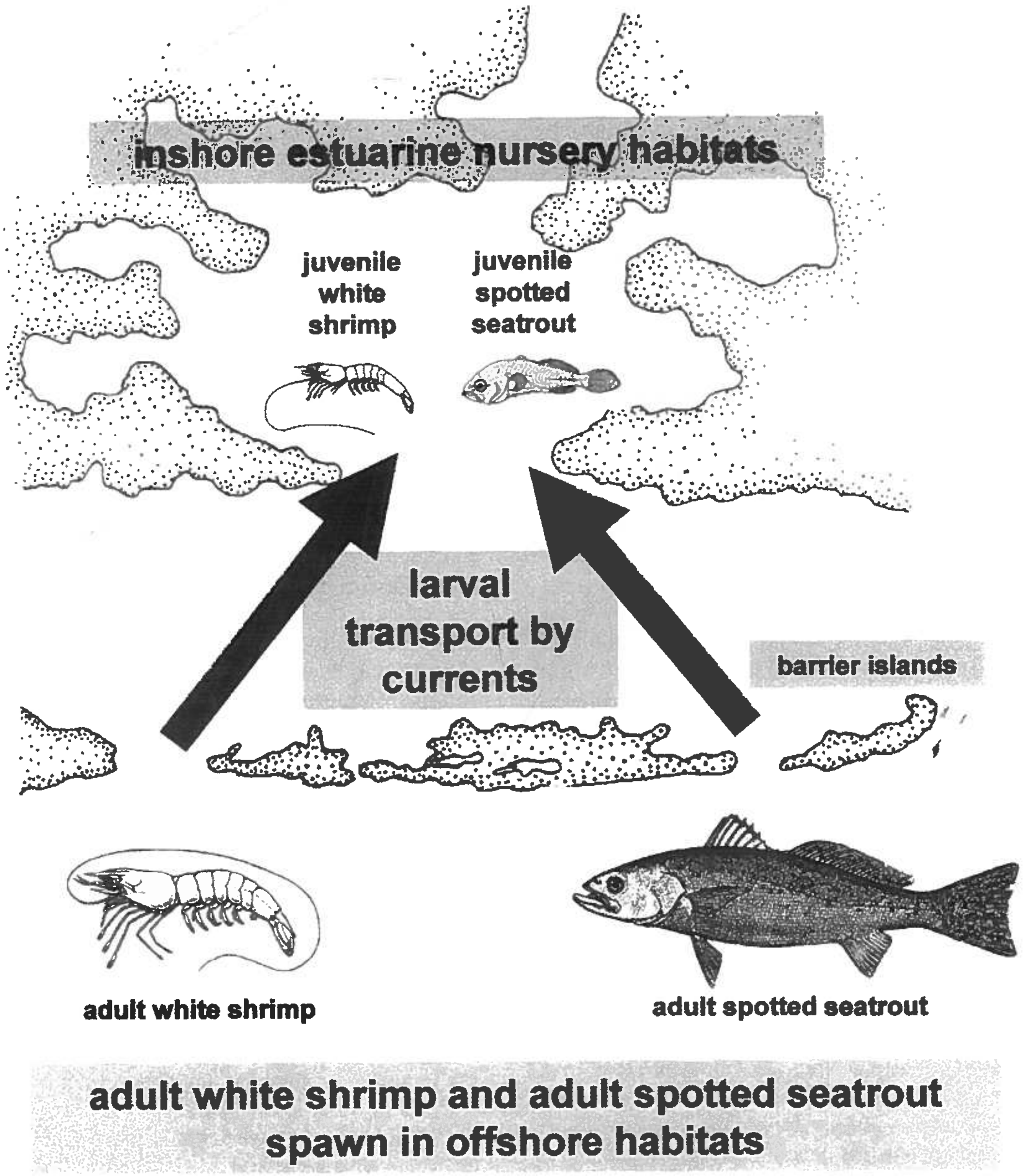

Figure 1. Many commercially important species including white shrimp and spotted seatrout are estuarine dependent, relying on timed use of inshore currents to transport their larvae to inshore estuarine nursery habitats. Shoreline change threatens the continued existence of these essential movement corridors. (Figure modified from the following: CHRISTMAS *et al.*, 1982; USFWS, 1984a; white shrimp drawings by Jeanne J. Hartley; USFWS, 1984b, adult spotted seatrout drawing by Pat Lynch; and juvenile spotted seatrout drawing by Bernd Ueberschär, redrawn from JOHNSON, 1978, and available at http://www.larvalbase.org.)

length of 70 to 90 mm (total length), juvenile brown shrimp tend to leave these shallow water habitats for deeper areas, and by the size of 90 to 110 mm they begin moving back to offshore Gulf habitats to spawn the following year (TURNER and BRODY, 1983).

Two elements of the brown shrimp's life cycle and habitat associations illustrate how this important species could be affected by shoreline change: its reliance on currents for movement and its preference for vegetated inshore habitats.

First, for such a small animal as the brown shrimp to travel many kilometers between offshore and inshore habitats over its lifetime, it must be reliant on drifting with currents for rapid transport. In light of this current dependence, consider the potential effects of current disruption on brown shrimp movement between offshore and inshore habitats as shoreline change transforms marshland and barrier island passes into shallow, open-water habitats (CHESNEY, BALTZ, and THOMAS, 2000). Passive transport across a shallow lagoon of homogeneous depths will be far less effective than using the currents that occur in inlets. These areas between land masses constrict flow, increase local current velocity, and can help animal movement either inshore or offshore (depending on wind direct and tides). As land loss increases, the numbers of these natural "chutes" decreases, limiting advection options for estuarine-dependent animals such as brown shrimp.

Second, even if brown shrimp larvae are successfully transported inshore from offshore breeding grounds, if there is no vegetated shallow habitat available (either emergent marsh or SAV), their survivorship is threatened (BROWDER *et al.*, 1989; MCTIGUE and ZIMMERMAN, 1991). Shoreline change has caused extensive loss of emergent marsh habitat throughout coastal Louisiana, and associated impacts (such as increased turbidity and current velocities) have contributed to declines in SAV throughout the state. As more of these habitats are lost, fewer juvenile brown shrimp in Louisiana will have access to adequate nursery habitat.

White shrimp are second only to brown shrimp in regard to crustacean fishery productivity in coastal Louisiana (CHESNEY, BALTZ, and THOMAS, 2000; ZIMMERMAN, MINELLO, and ROZAS, 2000). Like brown shrimp, white shrimp are estuarine dependent, using offshore habitats for spawning and inshore estuarine habitats for nurseries (TURNER and BRODY, 1983; ZIMMERMAN, MINELLO, and ROZAS, 2000). Because the life cycles and habitat associations of both species are somewhat similar, shoreline change threatens white shrimp populations for the same reasons it threatens brown shrimp populations. There are, however, some subtle differences in the biologies of these two species that may have led to white shrimp responding differently over time to shoreline changes than brown shrimp. In the northern Gulf of Mexico, white shrimp are considered to be more of an inshore species than the brown shrimp (MUNCY, 1984; TURNER and BRODY, 1983). For example, juvenile white shrimp occur further inshore in nursery habitats than do juvenile brown shrimp (TURNER and BRODY, 1983), and Louisiana white shrimp commercial landings are higher at inshore localities than offshore (MUNCY, 1984). White shrimp also move into estuaries later in the year than brown shrimp (entering western Gulf nursery habitats as late as May or June) (MCTIGUE and ZIMMERMAN, 1991) and appear less dependent on infaunal sources of animal prey items (KNEIB and KNOWLTON, 1995; ZIMMERMAN, MINELLO, and ROZAS, 2000).

These differences between the two species of shrimp are interesting in regard to shoreline change in that it has been suggested that a general increase in salinity over time has caused white shrimp populations along the northern Gulf to decrease relative to brown shrimp populations (CHRISTMAS and ETZOLD, 1977). Where once white shrimp dominated Gulf shrimp fisheries (until the 1950s), now brown shrimp yield the largest landings (ZIMMERMAN, MINELLO, and ROZAS, 2000). The implication is that the loss of coastal wetlands has allowed higher-salinity water to reach further inland than it has in the past. As inshore habitats become more saline, juvenile white shrimp will lose habitats that occur within their preferred salinity range of 1 to 10 ppt (MUNCY, 1984), while the amount of juvenile brown shrimp preferred salinity range of 10 to 20 ppt (TURNER and BRODY, 1983) will increase. Loss of inshore white shrimp habitat may be further accelerated because saltwater intrusion itself can kill marsh vegetation, leading to even more land loss and additional increases in salinity (DAY *et al.*, 2000). By understanding the differences in habitat preferences between these two important fishery species and then monitoring relative changes in their populations (or even landings) over time, we can show how shoreline change in Louisiana is having an impact on coastal biological resources.

The last invertebrate species we will discuss is the blue crab, a widespread animal that supports the largest crab fishery in the United States in both landings and value (FISHER, 1999). As with brown and white shrimp, blue crabs are estuarine dependent, but their life cycle and movements through estuarine habitats are somewhat more complex than those of the shrimp. Mating in blue crabs occurs in estuaries while the female is in the soft-shell state (GUILLORY, PERRY, and VANDERKOOY, 2001; PERRY and MCILWAIN, 1986). Females move to higher-salinity waters (>20 ppt) where eggs attached to their abdomen hatch into zoeal stages(GUILLORY, PERRY, and VANDERKOOY, 2001). Development into the megalope occurs in coastal waters and recruitment into estuaries occurs in this stage. Megalope develop into juvenile crabs in estuaries. Juvenile blue crabs can tolerate a broad range of salinity but are most abundant at low and intermediate salinities and prefer soft sediments (PERRY and MCILWAIN, 1986). Adults are also euryhaline but show sexual differences in salinity zonation. Males are common in low salinity and mature females in higher salinity of lower estuaries and coastal waters. This complicated life cycle means that blue crabs of different sexes and age classes can occur throughout all coastal salinity zones. JAWORSKI (1972) outlined five blue crab movement patterns that describe the life cycle and stages in Louisiana estuaries:

(1) in spring, large juveniles and males move from the lower estuary to the upper estuary;
(2) in late spring, small juveniles are recruited to the upper estuary;
(3) in summer, spawned females return from offshore habitats into the lower estuary;
(4) in autumn, gravid females move from the estuary offshore to spawn; and
(5) in winter, large juveniles and males move from the upper estuary to the lower estuary.

Along with being more general in their salinity tolerance than brown and white shrimp, blue crabs also have a more protracted spawning season. For example, most females spawn at least twice: once in spring and once in autumn (GUILLORY, PERRY, and VANDERKOOY, 2001), and it is possible during mild winters that spawning may occur year-round (DAUGHERTY, 1952). As with the shrimp species, though, blue crabs also exploit vegetated estuarine habitats, offering reduced predation threat and increasing food resources (THOMAS, ZIMMERMAN, and MINELLO, 1990; ZIMMERMAN, MINELLO, and ROZAS, 2000).

For blue crabs (and many other migrating animals) movement among many habitats throughout their life cycle is a way to reduce negative impacts from parasites. The less time

Table 2. *Ecological significance, habitats, and salinity conditions for selected keystone and other bivalve species found in coastal Louisiana. Alteration of salinity conditions by shoreline change could negatively affect any of these sedentary species.*

Common Name (Scientific Name)	Ecological Significance	Habitats and Salinity Conditions
American oyster[1] (*Crassostrea virginica*)	Creates reefs used by other organisms; filter feeds; prey item for numerous fishes	Optimal adult salinity range is 10–20 ppt[2]
Rangia clam[1] (*Rangia cuneata*)	Prey item for numerous fishes and waterfowl; filter feeds in oligohaline habitats	Optimal adult salinity range is 0–10 ppt; rapid salinity change triggers spawning[3]
Hard clam (*Mercenaria campechiensis*)	Filter feeds in estuarine habitats; provides hard substrate	Optimal adult salinity range is 20–26 ppt[3,4]
Dwarf surf clam (*Mulinia lateralis*)	Important food item for fish and wildlife	Habitats include bays and lagoons; wide salinity range[5]
Hooked mussel (*Ischadium recurvum*)	Important food item for fish and wildlife, especially ducks and other waterfowl	Habitats include low-salinity bays; needs hard substrate[5]
Bay scallop (*Argopectin irradians*)	Important food item for aquatic and terrestrial predators	Optimal adult salinity range is 16–35 ppt[3]

[1] Species described in text.
[2] CAKE (1983).
[3] PATILLO *et al.* (1997).
[4] HOPKINS *et al.* (1973); HOLLEY AND FOLTZ (1987).
[5] ANDREWS (1977).

an animal spends in one area or habitat, the less chance a potential parasite has to infest and harm the animal. Over 100 parasites, diseases, symbionts, and other animals have been reported to use blue crabs as hosts (GUILLORY, PERRY, and VANDERKOOY, 2001). In estuarine ecosystems, one simple method to escape these numerous parasites is to move into areas with salinities that are beyond the tolerance range of the infesting organism. For example, the parasitic dinoflagellate *Hematodimium perezi* occurs in the hemolymph of blue crabs but only in habitats with salinity greater than 11 ppt. The fact that male (occurring mostly in lower salinity habitats) and female blue crabs (occurring mostly in higher salinity habitats) commonly exhibit a gender bias in regard to parasite loads (*i.e.,* one sex has significantly more parasites than the other) is further evidence of this phenomenon (GANNON, WHEATLY, and EVERSON, 2001). As shoreline change turns formerly heterogeneous coastal habitats into homogeneous open water habitats and alters historic routes of blue crab movement, it can be expected that negative impacts of parasite infestations will increase. Degraded estuaries have several characteristics that have been shown to facilitate outbreaks of harmful parasites including physical confinement of crab populations that restricts immigration/emigration (as could happen if aquatic connectivity among habitats is eliminated) and reduced water exchange from open water to inshore backwaters (SHIELDS, 2001). It has also been shown that conditions in impacted habitats can cause increased stress on local organisms (*e.g.,* hypoxia, anoxia) making them more susceptible to secondary infestations (SHIELDS, 2001). Therefore, retaining a viable fishery of blue crabs in coastal Louisiana is greatly dependent on preserving habitats along a considerable salinity gradient whereby seasonal movements will allow the animals to avoid potentially harmful parasites.

As with these invertebrate species, most of coastal Louisiana's important fishes are also estuarine dependent and, by definition, require a variety of specific habitat conditions to complete their life cycles (CHESNEY, BALTZ, and THOMAS, 2000; THOMPSON and FITZHUGH, 1985). A loss of the geographic complexity under which these species evolved would threaten the existence of important feeding, spawning, and nursery habitats. Such anthropogenic habitat degradation and homogenization has resulted in significant decreases in fishery productivity in other estuaries throughout the world (MATERN, MOYLE, and PIERCE, 2002; PETERSON *et al.,* 2000; THAYER, THOMAS, and KOSKI, 1996; WASTE, 1996). Although many coastal fishes are estuarine dependent (Table 1), we will focus on the life cycles of three of Louisiana's most important estuarine fish species—the Gulf menhaden (*Brevoortia patronus*), the spotted seatrout (*Cynoscion nebulosus*), and the Atlantic croaker (*Micropogonias undulatus*)—such that their reliance on coastal habitats is clarified. As with brown shrimp, white shrimp, and blue crab, the vital ecological element for all these species is the ability to migrate among different habitats either as larvae (*e.g.,* larval transport), juveniles, or adults. An equally important aspect is that these different habitats need to provide different environmental conditions because the requirements of a larval fish are rarely comparable with those of an adult. For example, higher turbidity is likely to help larval and juvenile fishes (*e.g.,* decreases predation threat), while similar conditions would be detrimental to adult fishes trying to visually locate prey items (BALTZ, THOMAS, and CHESNEY, 2003). Without gradients of key environmental variables such as turbidity, salinity, and temperature, all estuarine habitats would be similar, and at least one phase of the life cycle of an estuarine-dependent fish species would not experience optimal conditions. As we discuss the life cycles of these three key fish species, we will emphasize these two elements, migration success and habitat differences along gradients, to link Louisiana gulf shoreline geographic complexity to fishery productivity.

The Gulf menhaden plays a unique role in that it not only dominates the total state landings in Louisiana fisheries but also is ecologically important, serving as a prey item for many predacious fish species throughout its life (CHESNEY, BALTZ, and THOMAS, 2000; HOESE and MOORE, 1998; VANDERKOOY and SMITH, 2002). Menhaden fisheries are some of the United States' most valuable, with these fishes being used mainly for oil, fish meal, and fish solubles, though a smaller bait fishery also exists in Louisiana (ROSS *et al.,* 2001; VANDERKOOY and SMITH, 2002). Louisiana leads the nation in regard to this fishery, with state menhaden landings representing 62% of all US menhaden landings and 11.6% of the total US catch of fish and shellfish in 1998 (VANDERKOOY and SMITH, 2002). The state also dominates the northern Gulf coast in regard to the industry of processing menhaden products, with four of the five regional plants being located in the coastal Louisiana cities of Empire, Morgan City, Abbeville, and Cameron (VANDERKOOY and SMITH, 2002). Like other important Louisiana fish species, Gulf menhaden are estuarine dependent, spawning in winter (November through February) in nearshore marine habitats where salinities are greater than 25 ppt, usually ranging between 30 and 36 ppt (CHRISTMAS *et al.,* 1982; SHAW, COWAN, and TILMAN, 1985). After spawning, buoyant Gulf menhaden eggs usually hatch with 48 hours (HETTLER, 1984), and the larvae move inshore where they spend the early part of their lives in habitats that are significantly different from spawning sites. Therefore, larval migration success and the availability of different estuarine habitats are essential to the Gulf menhaden's life cycle. Without exposure to the high current velocities associated with barrier island passes, Gulf menhaden eggs and larvae would never reach those inshore habitats where maximum survival depends on acquiring adequate food sources and minimizing predation (VANDERKOOY and SMITH, 2002). The environmental conditions found in these habitats that confer these benefits (*e.g.,* reduced depth, increased vegetation, and increased water color for avoiding predation) do not exist sympatrically in other habitats of the estuary (CHRISTMAS *et al.,* 1982; MINELLO and WEBB, 1997). This dependence on reaching and then exploiting the resources and conditions of a specific estuarine habitat suggests that physical alterations to estuarine geography (*e.g.,* shoreline change) that either remove or modify such habitats would negatively impact estuarine-dependent animals such as Gulf menhaden (HOSS and THAYER, 1993). The risk of jeopardizing the ecological processes of such an economically and ecologically important fish species through shoreline change and the rapid loss of barrier islands warrants at least minimal management attempts to maintain "normal" rates of geological change along the Louisiana Gulf shoreline.

Of all the important estuarine-dependent fish species in Louisiana, the spotted seatrout is by far the most popular food fish, supporting a thriving recreational fishery, and is the basis for a "way of life" for many angling residents (BALTZ, THOMAS, and CHESNEY, 2003). This highly piscivorous member of the family Sciaenidae (drums) is also ecologically significant in coastal Louisiana waters because it acts as one of the top predators, feeding on both shrimp and small fishes (BALTZ, THOMAS, and CHESNEY, 2003; BLANCHET *et al.,* 2001). Like the Gulf menhaden, spotted seatrout are highly reliant on achieving migration success and exploiting different habitat types throughout their life cycle (Figure 1). Selection of specific spawning habitat is particularly vital for spotted seatrout because areas of increased current velocities and depths appear to benefit reproduction (RUTHERFORD, SCHMIDT, and TILMANT, 1989). These two conditions apparently maximize egg dispersal (high current velocity) and decrease predation threat during spawning activity (increased depth). Although spawning can occur in the open waters outside of estuarine habitats, these spawning requirements mean that most spotted seatrout spawn in deep channels and passes such as those inlets found between barrier islands (BALTZ, THOMAS, and CHESNEY, 2003). Because these types of habitats are already limited in Louisiana's shallow estuarine habitats (BALTZ, THOMAS, and CHESNEY, 2003), the negative effect of barrier island alteration or loss on spotted seatrout reproduction would be significant. Without the physical presence of an island, landward currents would not be focused and increased in defined, restricted regions (*i.e.,* inlets), resulting in an overall reduction in tidal prism (HEALY, COLE, and DE LANGE, 1996) that would decrease the chances that drifting larval spotted seatrout would reach essential inshore habitats. This need for adequate larval dispersal also emphasizes the importance of where barrier islands occur relative to main shoreline: if the eggs are spawned too close or too far from these essential habitats, the timing of their development into larvae may be seriously affected. Even if larval spotted seatrout arrive at the main shoreline on time, a coast that has changed from being shallow and containing complex structural cover (*i.e.,* emergent vegetation) to being a high-energy, featureless ecotone between land and water (as would happen with the loss of protective barrier islands) would not provide adequate environmental conditions (BALTZ, THOMAS, and CHESNEY, 1993; RAKOCINSKI, BALTZ, and FLEEGER, 1992). The continued ecological success of this species in Louisiana is highly dependent on some degree of geological continuity of the Gulf shoreline's barrier islands and inshore marshes.

Another important estuarine-dependent member of the drum family is the Atlantic croaker. Unlike the spotted seatrout, the Atlantic croaker is much more of a generalist in regard to its use of spawning and nursery habitats. It spawns not only in tidal passes but also in the mouths of estuaries and even deep continental shelf habitats (ABLE and FAHAY, 1998; DIAZ and ONUF, 1985). Even at the recruitment stage, the Atlantic croaker is a habitat generalist, using both vegetated and unvegetated nursery habitats (PETRIK *et al.,* 1999). Having less specific habitat requirements than the Gulf menhaden and the spotted seatrout should make the Atlantic croaker less vulnerable to threats from shoreline change, but the sizable contribution that Atlantic croaker make to Louisiana fisheries demands that the connection between their estuarine-dependent life cycle and potential shoreline change be examined. This numerous species is economically important to coastal Louisiana because it is harvested commercially for canned pet food and widely used as live bait (NMFS, 1999). For example, the Atlantic croaker was the second most numerous finfish collected in long-term fishery-independent sampling surveys in coastal Louisiana (CHESNEY, BALTZ, and THOMAS, 2000). The breadth of importance of the Atlantic croaker is revealed in that in the fisheries of the United States, it is the only fish species that

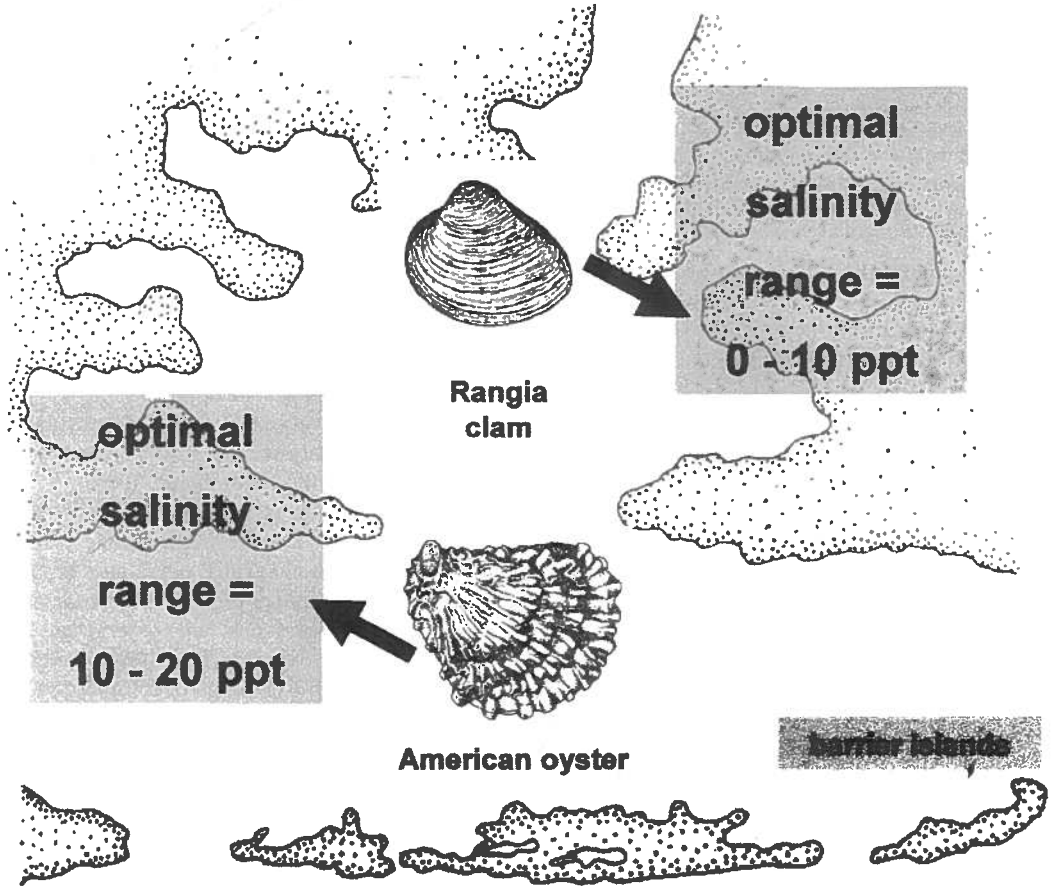

Figure 2. Keystone species such as the American oyster and the Rangia clam are sedentary as adults and occur in specific salinity zones. Shoreline change threatens to alter the salinity gradient, changing salinity conditions in these animals' habitats. (Figure modified from the following: CHRISTMAS *et al.*, 1982; USFWS, 1985a; Rangia clam drawing by Jeanne J. Hartley; and USFWS, 1984c; American oyster drawing by Pat Lynch.)

occurs in the top 10 most abundant fish species caught for both commercial and recreational harvests in 2001 (NMFS, 2002). Such a numerous species is not likely to become extinct as a result of shoreline change, but retaining high population sizes in the face of changing habitat conditions could become a problem. For example, it has been shown that juvenile Atlantic croaker grow significantly faster in lower salinities (*i.e.* 5 ppt) versus higher salinities up to 20 ppt (PETERSON *et al.*, 1999). As with the white shrimp, if shoreline changes lead to higher salinities for inshore nursery habitats in Louisiana, it can be expected that this will negatively affect the growth and populations of Atlantic croakers. With this and other estuarine-dependent species, the main threat that wetlands loss poses is a reduction of habitat options. Although fishery productivity for many of these commercially important species has yet to be affected by shoreline change (CHESNEY, BALTZ, and THOMAS, 2000; ZIMMERMAN, MINELLO, and ROZAS, 2000), as wetlands and the edge habitat they provide disappear, less juvenile animals will survive to contribute to coastal populations. Maintaining the greatest amount of estuarine habitat possible is the most effective method for maintaining viable fishery populations.

KEYSTONE SPECIES AND SALINITY CONDITIONS

While estuarine-dependent species rely on their mobility to exploit various habitats during their life cycles, other coastal animals are sedentary during their adult stages and depend solely on the resources that occur in their local habitats. In coastal Louisiana, the most common of these benthic animals include the American oyster (*Crassostrea virginica*), the Rangia clam (*Rangia cuneata*), the hard clam (*Mercenaria campechiensis*), the dwarf surf clam (*Mulinia lateralis*), and the hooked mussel (*Ischadium recurvum*). These and other benthic animals (mostly bivalve mollusks) are distributed in different zones along a coastal salinity gradient ranging from fresh to full-strength seawater (Table 2). In their local communities these benthic species provide multiple ecological services to other ecosystem members. Their filter feeding increases local water quality and produces valuable by-products such as pseudofeces. Many benthic organisms are prey items for important estuarine animals such as blue crabs and black drum (*Pogonias cromis*). Finally, their shells provide habitats and valuable hard surfaces for other organisms to exploit in a coastal ecosystem dominated by sand and mud substrates. To demonstrate the value of benthic organisms to Louisiana, we will examine the biology and habitat associations of two keystone species: the American oyster and the Rangia clam. Both animals are considered keystone species in their respective salinity zones because their presence and numerical dominance determines the overall functioning of the local community. Without viable populations of American oysters and Rangia clams, many coastal Louisiana aquatic habitats would lose significant amounts of biodiversity and biomass.

Beyond its ecological value, the American oyster is also a vastly important commercial species for Louisiana and the entire nation. In the United States, oysters are considered a luxury food item, and the oyster industry provides thousands of fishery and processing jobs (MACKENZIE, 1996; STANLEY and SELLERS, 1986). Because oysters occur in estuaries, their nearness to coastal human populations has made them a useful food item for over 10,000 years (GOODYEAR and WARREN, 1972). Unfortunately, this closeness to coastal development also makes oysters more vulnerable to human-induced habitat alteration (STANLEY and SELLERS, 1986). For example, artificial changes in local salinity conditions can be extremely detrimental to oyster populations. Under natural conditions, salinity and the presence of a hard surface to settle on determines the distribution of oysters. They can survive salinities of 5 to 40 ppt, but their optimum salinity range is about 10 to 20 ppt (Figure 2) (CAKE, 1983). This means that although oysters occur throughout coastal Louisiana, they are absent in limnetic and oligohaline salinity zones. Oyster distribution into low-salinity waters is limited by physiological tolerance, whereas their abundance in high-salinity waters is affected by competition, predators, and disease. For instance, the oyster drill (*Stramonita hemastoma*) is an important oyster predator but does not tolerate salinity below 15 ppt. Therefore, occasional decreases in salinity below 15 ppt are beneficial because they control drills, other predators, and disease. If salinity conditions are within this suitable range, the next requirement for the survival of dispersing larval oysters is the presence of a firm substratum on which to attach. Usually this hard surface is a preexisting oyster reef consisting of living adult oysters and the shells of previous oysters (DARDEAU *et al.,* 1992). The need for a firm substratum is so important that if no hard substratum is present, oyster managers and workers will place cultch (*i.e.,* old shells and other hard substances) on soft bottoms to help culture oysters in local habitats. Therefore, the continued success of this valuable fishery species in Louisiana is highly linked to the maintenance of a specific salinity range and the presence of hard substrates.

Based on these habitat constraints, it is important to consider how oysters will respond if shoreline modification in Louisiana leads to altered salinity zones in estuaries. This issue has already generated extensive debate and litigation involving the effect of river diversion projects on the oyster fishery. River diversion projects lower the salinity at established oyster reefs, displacing the historic fishery to habitats further offshore. Significant shoreline change could displace oysters in the opposite direction if the loss of protective wetlands leads to further saltwater incursion. The problem is that oyster reefs cannot become established and serve as the preferred hard substrate for future larval oysters without the local salinity range remaining relatively stable over a long period (STANLEY and SELLERS, 1986; TURNER *et al.,* 1994). As coastal salinity increases with wetlands loss, the optimal salinity range for oysters (10–20 ppt) will occur further inland over time. If the optimal salinity range occurs only in an area where hard substrates are not available (*e.g.,* parts of the estuary where historic oyster reefs do not exist), then dispersing larval oysters will be limited by a lack of suitable habitat. It is further possible that these new inshore areas will lack adequate food resources (*i.e.,* algae, bacteria) and the water currents to deliver these resources to the filtering oysters. Such a salinity-based response would be consistent with what has been shown in other estuaries where the position of particular salinity zones has a direct relationship with the success of local estuarine organisms (JASSBY *et al.,* 1995; PATILLO, ROZAS, and ZIMMERMAN, 1995).

The Rangia clam is another keystone estuarine species of Louisiana whose distribution is strongly dependent on local salinities. This ecologically (and once economically) important species dominates oligohaline estuaries, being replaced by other bivalves (such as oysters) at higher salinities (MOORE, 1992). It occurs in mud and sand bottoms, has an optimal adult salinity range of 0 to 10ppt (Figure 2), and is absent at salinities above 25 ppt (HOPKINS *et al.,* 1973). Salinity also plays a role in the spawning of Rangia clams. Spawning is triggered by an increase or decrease in salinity, and fertilized eggs develop into planktonic larval stages that are dispersed by currents (LASALLE and DE LA CRUZ, 1985). Once these stages settle into a habitat and transform into adults they will move very little from that location (LASALLE and DE LA CRUZ, 1985). Because Rangia clams can attain high densities (up to 128 individuals/m^2) in oligohaline estuaries (MOORE, 1992), they serve many important roles in the aquatic community. Along with providing a hard substrate under conditions where American oysters cannot survive, by feeding on detritus and algae Rangia clams are the main link between primary and secondary consumers (LASALLE and DE LA CRUZ, 1985). They are an abundant diet component of key oligohaline fish species such as spot (*Leiostomus xanthurus*), black drum (*Pogonias cromis*), blue catfish (*Ictalurus furcatus*), and freshwater drum (*Aplodinotus grunniens*) (DARNELL, 1961). The ecological connections between Rangia clams and other members of the oligohaline community mean that salinity changes that affect Rangia clam populations will also influence populations of those organisms that depend on them, either as prey items or as hard surfaces.

In some oligohaline estuaries where salinity has been artificially altered, the negative impact on Rangia clams has already been demonstrated (ABADIE and POIRRIER, 2000; HARRREL, 1993; PATILLO, ROZAS, and ZIMMERMAN, 1995). A typical example involves Rangia clam populations in Louisiana's Lake Pontchartrain, the largest oligohaline estuary in the southeastern United States (MOORE, 1992). This estuary has been subject to numerous anthropogenic impacts over the past half century, including urban and agricultural runoff, shell dredging, overfishing, artificial saltwater and freshwa-

Table 3. *Federally threatened and endangered species found in coastal Louisiana (LA) that are dependent on or use barrier island habitats.*

Common Name (Scientific Name)	Federal Status	Dependence on Barrier Islands
Gulf sturgeon[1] (*Acipenser oxyrinchus desotoi*)	Threatened	Feeds in shallow water habitats associated with barrier islands, particularly passes
Brown pelican[1] (*Pelecanus occidentalis*)	Endangered	Uses barrier islands for nesting and nearby aquatic habitats for feeding
Piping plover[1] (*Charadrius melodus*)	Threatened	Uses barrier islands as wintering habitats because of reduced predation pressure
Hawksbill sea turtle[1] (*Eretomchelys imbricata*)	Endangered	Needs warm, shallow aquatic habitats for feeding
Kemp's ridley sea turtle[1] (*Lepidochelys kempi*)	Endangered	Needs warm, shallow aquatic habitats for feeding
Leatherback sea turtle[1] (*Dermochelys coriacea*)	Endangered	Needs warm, shallow aquatic habitats for feeding
Green sea turtle[1] (*Chelonia mydas*)	Threatened	Needs warm, shallow aquatic habitats for feeding
Loggerhead sea turtle[1] (*Caretta caretta*)	Threatened	Nests on barrier islands; needs warm, shallow aquatic habitats for feeding
Bald eagle (*Haliaeetus leucocephalus*)	Threatened	Not dependent on barrier islands but will use terrestrial habitats on islands for nesting
West Indian manatee (*Trichechus manatus*)	Endangered	Not dependent on barrier islands but will use warm, shallow aquatic habitats for feeding

[1] Species described in text.

ter inputs, shoreline alteration, and industrial discharges (FRANCIS and POIRRIER, 1999; MOORE, 1992; PENLAND *et al.*, 2002). Of these problems, the widespread and long-term (from the 1930s to the 1990s) dredging of Rangia clams for use as road and driveway building material was arguably the most detrimental to the estuary. For example, from the 1950s to 2000, demersal fish assemblages changed markedly in Lake Pontchartrain. Benthic fish species such as Atlantic croaker and spot that rely heavily on the presence of Rangia clams have become less dominant in trawl samples over time (O'CONNELL, CASHNER, and SCHIEBLE, 2004). After shell dredging ceased in 1990, though, densities of large Rangia clams have increased in the estuary, suggesting that populations are recovering (ABADIE and POIRRIER, 2000). Unfortunately, this recovery has been curtailed in the southeastern region of Lake Pontchartrain, where high-salinity bottom water has entered the estuary through an artificial connection completed in 1963 (ABADIE and POIRRIER, 2000). This saltwater intrusion produces salinity stratification and episodic benthic hypoxia that can kill resident Rangia clams and other benthic organisms (ABADIE and POIRRIER, 2000). For full recovery of Rangia clams throughout Lake Pontchartrain, the artificially elevated salinities found in the southeastern region need to be reduced to levels more consistent with a natural oligohaline estuary (fresh −5 ppt).

This "real world" example of how altered salinity can have profound effects on an estuary demonstrates that shoreline change resulting in salinity shifts could be highly ecologically detrimental to coastal Louisiana. Although both Rangia clams and American oysters are keystone species that support the entire estuarine community in their particular zones of salinities, the sedentary nature of both species during adult stages makes them particularly susceptible to sudden artificial changes in salinity. If wetlands continue to be lost and the length of the salinity gradient from freshwater to saltwater keeps shortening, then there will be fewer habitat options for these two keystone species. A loss or significant reduction in either species will have severe consequences for all estuarine species.

SPECIES AT RISK AND BARRIER ISLANDS

Beyond these keystone and commercially important species that dominate the biomass of Louisiana's estuaries, there are also other less numerous species that occur along the coast that are directly threatened by shoreline change. For these rare species, the loss of barrier islands is the primary problem because these islands provide protected, isolated habitats that cannot be found elsewhere along the coast. The link between species at risk and barrier islands is reflected in the fact that of the 10 federally threatened and endangered species that occur in coastal Louisiana, eight have direct ties to barrier island habitats (Table 3). These eight species are the Gulf sturgeon (*Acipenser oxyrinchus desotoi*), the brown pelican (*Pelecanus occidentalis*), the piping plover (*Charadrius melodus*), and five species of sea turtles: the hawksbill (*Eretomchelys imbricata*), the Kemp's ridley (*Lepidochelys kempi*), the leatherback (*Dermochelys coriacea*), the green (*Chelonia mydas*), and the loggerhead (*Caretta caretta*). The remaining two rare species, the bald eagle (*Haliaeetus leucocephalus*) and the West Indian manatee (*Trichechus manatus*), may also use habitats associated with barrier islands but are not strictly dependent on them. If barrier islands are lost because of anthropogenic alteration or lack of sufficient sand input over the next century, these are the eight species that will be most negatively affected because they rely on barrier islands for nesting, breeding, and feeding. For these species it is the unique physical isolation provided by islands that draws them to preferentially use these habitats, either because of the reduced predation pressure offered by islands or because of their distance from human-altered regions located on the main shoreline. We will review how these eight rare species are associated with barrier island habitats and discuss how shoreline change threatens their continued existence in coastal Louisiana.

The federally threatened Gulf sturgeon is a large (top estimated weights of 272 kg), rare fish species found only in the Gulf of Mexico, including areas of coastal Louisiana. Because it is anadromous, it uses coastal rivers as spawning habitats, then moves to estuarine habitats around barrier islands to forage (HEISE *et al.,* 2004). Recent evidence shows that these barrier island habitats are particularly important to the Gulf sturgeon because it feeds exclusively on food items found along the sand substrate at barrier island passes (GU *et al.,* 2001; ROSS *et al.,* 2001). The unconsolidated, fine- to medium-grain sands found in these habitats support known prey items for the Gulf sturgeon such as lancelets, small crustaceans, and amphipods (KELLY and LEE, 2002; ROSS *et al.,* 2001). According to recent telemetry data collected from estuarine habitats in Louisiana and Mississippi, foraging adult Gulf sturgeon overwinter in the area between barrier islands and the main shoreline, with no evidence of offshore feeding migrations to marine habitats in the Gulf of Mexico (KELLY and LEE, 2002; ROGILLIO, personal communication; ROSS *et al.,* 2001). These shallow and productive habitats created and protected by barrier islands are essential for the Gulf sturgeon to complete its life cycle. Any further negative impacts or degradation caused by shoreline change could bring this species closer to extinction because of its already significantly reduced population numbers and the extensive degradation of its freshwater spawning habitats (ROSS *et al.,* 2001). If the Gulf sturgeon is to remain a part of Louisiana's fish community, then barrier islands need to be maintained.

The federally endangered brown pelican has already suffered extirpation from Louisiana (albeit temporary) and is perhaps the most important species in regard to representing the need for coastal preservation. The original Louisiana populations of brown pelicans were extirpated in the 1960s because of ingestion of DDT compounds from prey fishes (USFWS, 1995a). Since then, brown pelicans have been reintroduced to the state from Florida, and recovering populations have established nesting colonies on North Island in St. Bernard Parish, Queen Bess Island in Jefferson Parish, and Isle Dernieres in Terrebonne Parish and along the Mississippi River in Plaquemines Parish (LDWF, 1993). While the threat of extinction or extirpation from chemical contamination has for the most part passed, recovering populations of the Louisiana state bird face the loss of necessary marsh and barrier islands habitats (HINGTGEN, MULHOLLAND, and ZALE, 1985) because of widespread intensive coastal erosion. For example, barrier island nesting sites provide brown pelicans (and other colonial nesting birds) with habitats that are free of most if not all possible mammalian egg predators (Figure 3) (USFWS, 1995a, 1995b). If these habitats were to be lost, then the continued recovery of reintroduced brown pelican populations in Louisiana would be put at risk. Also, loss of barrier island and marsh habitats would negatively impact populations of coastal fishes, the primary food source of brown pelicans.

The major contributors to the decline of the federally threatened piping plover are the loss and degradation of its beach habitat due to anthropogenic impacts (USFWS, 1996). In Louisiana, the piping plover winters on coastal beaches, with barrier islands representing the majority of critical habitats available in the state (CORBAT and BERGSTROM, 2000; HAIG, 1992; JACKSON and JACKSON, 2000; LOWERY, 1974; NOL and BLANKEN, 1999; PAGE *et al.,* 1995; PAULSON, 1995). As with the brown pelican, predation is a major factor limiting piping plover reproductive success, especially in habitats that are not isolated from mainland mammals such as raccoons and dogs (USFWS, 1996). Therefore, disappearing barrier islands represent areas where predation threat is reduced and may also provide another benefit to piping plovers: people-free beaches. The presence of humans near piping plover habitats has been shown to significantly reduce foraging success of the birds (BURGER, 1994). When humans are not present, though, piping plovers can devote most of their time (*ca.* 90%) to feeding (BURGER, 1994). This trend of piping plovers avoiding people has been observed throughout its distribution (USFWS, 1996). For example, when beach sections were closed to pedestrian recreation at Trustom Pond National Wildlife Refuge in Rhode Island, within 2 years piping plovers had colonized the area (USFWS, 1996). The implication is that for piping plovers (and likely many other bird species in Louisiana), barrier islands provide habitat that is not easily accessible by people, and this is beneficial to the birds. Every barrier island lost to coastal erosion and shoreline change reduces the possibility of piping plovers remaining in the state.

The sea turtles found in estuarine and marine waters represent the largest group of federally threatened and endangered coastal animals in Louisiana. The hawksbill, Kemp's ridley, and leatherback sea turtles are listed as federally endangered, while the green and loggerhead sea turtles are listed as federally threatened (NMFS, 1999). All these species are threatened by overharvesting, bycatch mortality from other fisheries, and habitat destruction, but federal recovery plans are in place to assist in managing the continued survival of these species (NMFS, 1991a, 1991b, 1992, 1993; USFWS, 1993). In Louisiana, the only area where the five sea turtle species occur is in coastal regions with barrier islands providing the most habitats for feeding and nesting. In general, sea turtles will exploit vegetated shallow habitats for feeding when available and use beach habitats for nesting, though differences in habitat needs exist among the species. Most habitat use in Louisiana is associated with feeding with only one of these species, the loggerhead sea turtle, using beach habitat for nesting (Figure 3). The hawksbill sea turtle is infrequently encountered in Louisiana because it apparently does not nest in state waters but may feed in warm, shallow marine and estuarine habitats on sponges and encrusted organisms (NMFS, 1993). Like the hawksbill sea turtle, the Kemp's ridley sea turtle does not nest in Louisiana, but it is found more often than the hawksbill in state waters, likely because of its preference for turbid, highly productive nearshore habitats that provide key prey items like crabs, gastropods, and clams (DOBIE, OGREN, and FITZPATRICK, 1961; USFWS, 1993). The productivity of Louisiana coastal habitats explains why this area contains the major feeding grounds for subadult and adult Kemp ridley turtles (HILDE-

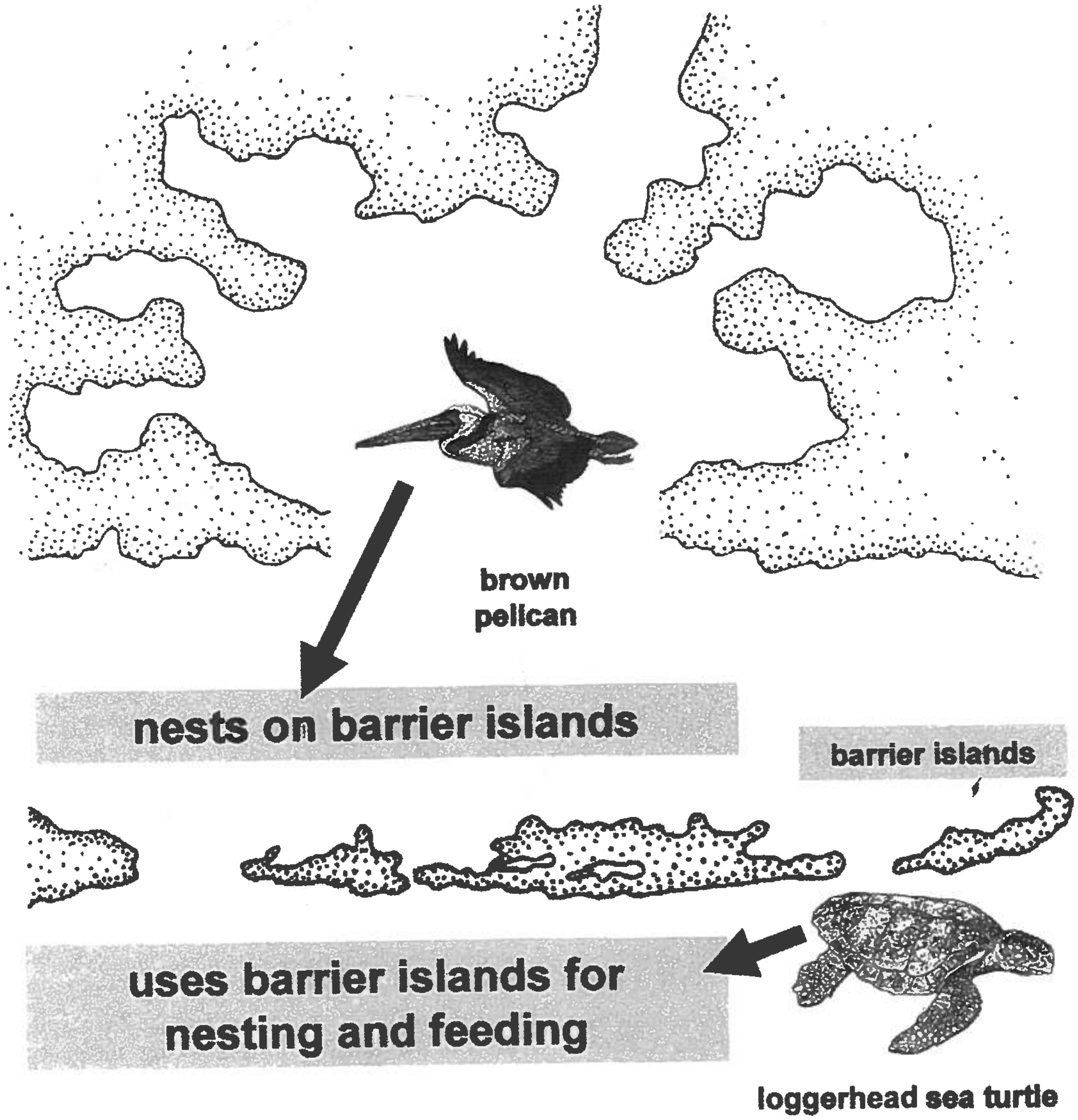

Figure 3. Federally threatened and endangered species including the loggerhead sea turtle (threatened) and the brown pelican (endangered) use barrier island habitats for feeding and nesting. The isolation of these islands provides habitats with reduced predation pressure for these animals. (Figure modified from the following: CHRISTMAS *et al.,* 1982; USFWS, 1985b; brown pelican drawing by Pat Lynch; and NMFS/USFWS, 1991: loggerhead sea turtle.)

BRAND, 1981). Leatherback sea turtles are the most pelagic of the sea turtles and have not been reported to nest on Louisiana (NMFS, 1992). Although they may rarely occur along the entire Louisiana coastline, their feeding preference for jellyfishes could attract them to shallow, barrier island habitats. Similarly, the green sea turtle enters Louisiana estuaries only to feed but may be more sensitive to estuarine change because it feeds on submersed aquatic vegetation, which rarely exists outside of shallow, clear water habitats (NMFS, 1991a). The only species known to nest in Louisiana is the loggerhead, with female turtles selecting high-energy beaches on barrier strands adjacent to continental landmasses (NMFS, 1991b). The Chandeleur Islands contain the only known nesting sites, and the factor most likely limiting the species in Louisiana is loss or degradation of suitable nesting beach habitat (OGREN, 1977). The diet of loggerhead sea turtles also suggests these animals benefit from feeding on mollusks, crabs, shrimp, and other invertebrates common to the state's shoreline and barrier islands (NMFS, 1991b). Without barrier islands and the productive estuarine habitats protected by these islands, sea turtles, the most threatened marine animals in Louisiana, would have little if any required habitat within the state.

To grasp the importance of barrier islands to these rare species, one needs only to consider what would happen if all of Louisiana's coastal islands disappeared: Gulf sturgeon would have no winter feeding grounds, brown pelicans and piping plovers would be forced to use suboptimal nesting habitat, and sea turtles would have to find shallow, vegetated feeding habitats in other states. Although we have focused our discussion on federally threatened and endangered animals, there are many other more common coastal animals that would also be negatively impacted by barrier island loss, including commercially important fishes (*e.g.,* red drum). In pursuing coastal restoration, managers need to recognize that although barrier islands represent a small proportion of the total available shoreline, the ecological conditions created by their isolation from the mainland make them invaluable to all estuarine animals.

CONCLUSIONS

It is clear from these descriptions of Louisiana coastal animals and their habitat associations that many important biological resources depend on the estuarine ecosystem. Rapid shoreline change is the largest threat to this ecosystem in that loss of coastal land will lead to altered movement corridors for estuarine-dependent animals, changes in salinity zones, and the disappearance of barrier island habitats. The level of complexity in any estuary precludes simple predictions of how species will respond to habitat alteration. In assessing Louisiana's coastal fisheries, CHESNEY, BALTZ, and THOMAS (2000) described the difficulty in attributing any one cause to estuarine fishery trends because so many ecological changes have occurred simultaneously along with shoreline change (*e.g.,* increased fishing pressure, presences of invasive species, and so on). Likewise, ROSE (2000) found that when multiple stressors act on complex ecosystems, species may respond in "nonintuitive" or unpredictable ways. For example, if a species loses feeding habitat to shoreline change in one part of the estuary, this impact may be countered by a decrease in predation pressure in another area (*i.e.,* the predator is affected more by habitat change than the prey). These complicated relationships make shoreline change that much more of a threat to ecosystem stability in that we cannot predict which action could cause the whole network to collapse. In the least, the continued loss of land along the coast greatly complicates any attempts to successfully manage the biological resources of this productive area.

This inherent ecological complexity is also the reason why many of the important species we have discussed cannot be confined to just one of our three broad categories. Commercially important fish species that are estuarine dependent such as the Gulf menhaden and the Atlantic croaker can also be considered keystone species in these estuaries because of their tremendous numbers and the role they play as prey for other fishes. If populations of either of these species significantly increased or decreased because of changes in fishing pressure, the effects would be evident throughout the food web. The American oyster is also both a keystone species and a commercially important resource. Humans and some fish species such as black drum (SUTTER, WAILER, and MCILWAIN, 1986) directly compete to consume oysters, suggesting that if one of these predators was removed, the other would benefit. The unfortunate effects of a species being both commercially important and an ecological keystone were made clear when years of shell dredging for Rangia clams in Lake Pontchartain contributed to the widespread degradation of this estuary (ABADIE and POIRRIER, 2000). Even the federally threatened Gulf sturgeon can be regarded as somewhat estuarine dependent (*i.e.,* using estuaries as movement corridors to freshwater spawning habitats) and has in the past supported short-lived commercial fisheries in the Gulf of Mexico (ROSS *et al.,* 2001). The point is that these species play multiple roles in creating the aquatic productivity of Louisiana's coast with each species experiencing pressure from both natural and anthropogenic forces. Habitat loss and alteration caused by shoreline change will only amplify uncertainty in the continued existence of functioning estuaries. Minimizing rapid land loss will give managers more flexibility to properly administer these complex systems; that is, there will be one less confounding factor affecting the populations of these animals.

Beyond the issue of shoreline change increasing the ecological complexity and instability of estuaries, it should be clear that coastal land loss more directly means habitat loss for these important biological resources. The importance of organisms having habitat available is demonstrated in the fact that habitat loss is the leading cause of species extinction over the past century (PIMM and RAVEN, 2000). While it is easy to recognize that without barrier islands many birds and sea turtles will lose nesting and foraging habitat, the less obvious fact that loss of land also affects important aquatic animals was illustrated in our discussion of species' habitat associations. It is not enough to say shrimp, crabs, and fishes need water to survive. These animals need a variety of aquatic habitats with different depths, current velocities, vegetation amounts, and salinities. An island or a point that blocks wave energy and creates shallow water areas on its low-energy side also helps form a gradient of shallow to deep aquatic habitats. This depth gradient, in turn, allows a wider variety of aquatic organism to occupy this space, with smaller organisms such as juvenile fishes and shrimp using the shallow water and larger animals such as sharks and red drum using the deeper water. Loss of this island or point means that the surrounding aquatic habitat becomes much more homogeneous and that the various microhabitats with their specific environmental conditions disappear. By protecting coastal wetlands from land loss, essential aquatic habitats such as fish nursery grounds are also protected.

It is in this context that these animals and their habitats must be considered in relation to coastal restoration activity in Louisiana. Both the slowing or stopping land loss through managed river diversions and the protection of eroding barrier islands help the long-term prospects of biological resources in the state. As river sediments are reintroduced into estuaries, more vegetation can become established, creating more wetlands and therefore more protected aquatic habitat. Slowing the rate of barrier island erosion through maintenance efforts allows these structures to continue protecting inshore structures and shallow aquatic habitats until natural sand replenishment rates are established again. We recognize that in such a geologically dynamic area as coastal Louisiana, structures like barrier islands and marshes are not considered permanent features of the system under natural conditions. All estuarine species have evolved to adjust to slow changes in these habitats where barrier islands migrate inshore over geologic time and marshes slowly change vegetative composition in response to changes in sea level. But the current shoreline change represents an artificially rapid rate of habitat alteration, and we cannot assume that all local organisms possess the adaptive plasticity to continue to thrive under these changing conditions. Therefore, efforts such as river diversions and barrier island protection offer the best protection for these animals and their habitats while resource managers attempt to reverse the trend of land loss. Any successes in slowing the rate of land loss will help these species remain as functioning parts of the coastal ecosystem until more natural processes can, it is hoped, be restored sometime in the future.

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